# All Terrain Exploration with the Cliff-bot System*


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***Abstract* - The Cliff-bot system consists of three individual planetary rovers that work as a team to explore the surface of a cliff. Two of the rovers, designated "Anchor-bots" assist the motion of a third rappelling "Cliff-bot" down and along a cliff face using tethers. A decentralized control technique is used to control the motion of the three rovers. The objective of this study is to develop several control algorithms that will create a robust and reliable Cliff-bot system. Control is accomplished by combining and prioritizing several different control algorithms into a hybrid deliberative-reactive control structure. Many different algorithms have been successfully developed and tested to provide the Cliff-bot system with stable and robust navigation of terrain slopes of at least 70 degrees.**



***Index Terms - Cooperative Control, Mobile Robotics, All Terrain Exploration, Planetary Exploration.***


## I. Introduction

Many robotic concepts have been proposed to increase the effectiveness of planetary exploration [1,2]. Some robot teams have been proposed for tasks such as the construction of outposts and the exploration of high-risk terrain. Concept and development of robotic systems for these particular tasks is being performed by the Mobility System Concept Development Section at the Jet Propulsion Laboratory (JPL).

In the construction of outposts, rovers will be sent to a body such as Mars and perform preparatory tasks prior to the arrival of humans. One such task involves the construction of a photovoltaic tent array for generating electrical power. This task will be accomplished through the use of the Robotic Work Crew [1].

Exploration of high-risk terrain will provide scientists with the ability to study areas such as escarpments, fissures, breakout channels, cliffs, and steep crater walls. The proposed robotic system for this task is the Cliff-bot system [2]. This system will provide scientists access to exposed stratified geographic regions. Such regions are generally on extremely steep terrain that is inaccessible to current robotic technology. Past explorations have shown on several occasions that exposed regions contain extensive information regarding the planets history. For instance, when searching for fossils on Earth, the most accessible sites are traditional geological exposures such as cliff faces [3].

## II. Cliff-bot Description

To give the Cliff-bot system the mobility to explore high-risk areas safely, the system consists of three rovers. These rovers work together, as a team, in a tightly coordinated motion. Two of these rovers, designated as "Anchor-bots", post themselves at the top of a cliff or canyon wall. These two rovers are tethered to the third rappelling rover, designated as "Cliff-bot". The "Anchor-bots" use winches to control the tension in the tethers and assist the rover with motion in any direction along the surface of the cliff or canyon wall. A standard configuration of the Cliff-bot system is shown in Fig. 1.

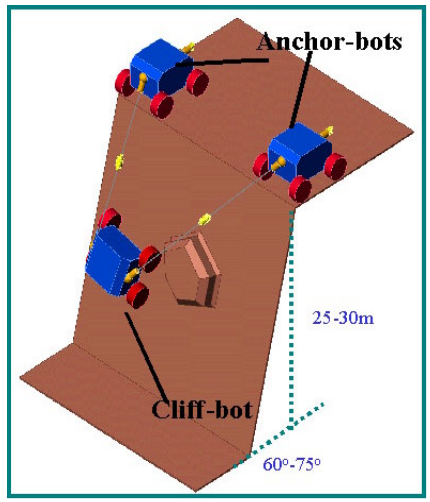


Fig. 1 Configuration of Cliff-bot System [4].

## III. Mechanical Hardware

At JPL, the system hardware consists of two winches, each mounted on a one d.o.f. rail, and the Sample and Return Rover 2000 (SRR2K) [4]. The two winches are used to emulate the "Anchor-bots" and the SRR2K rover is used to emulate the rappelling "Cliff-bot". At this time the "Anchor-bots" are not completely mobile. This has not been necessary for demonstrating mobility on steep surfaces. For instance, this system has successfully navigated natural terrain with slopes greater than 60 degrees [4]. However, to continue to progress in the development of the Cliff-bot system, it will be necessary to have fully mobile "Anchor-bots". An image of the JPL system is shown in Fig. 2.


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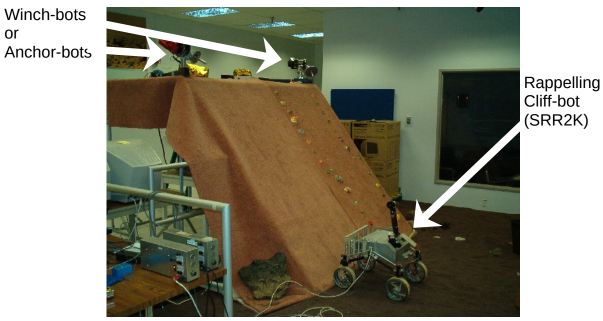


Fig. 2 Cliff-bot system at JPL.

To better assist the effort of developing the Cliff-bot system, the University of Nebraska-Lincoln (UNL) has also built a Cliff-bot system. This system is in the process of being upgraded to a fully functional state. A fully functional state includes the use of three fully mobile rovers. The UNL Cliff-bot system, shown in Fig. 3, consists of one mobile 5 kg class rover and two stationary “Anchor-bots”. However, two additional rovers, shown in Fig. 4, have been designed and are currently being built. These two rovers will allow for the development of more complex control algorithms.

Fig. 3 UNL Cliff-bot system.

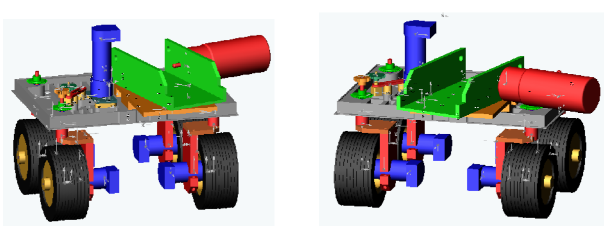

Fig. 4 “Anchor-bots” designed for the UNL Cliff-bot system.

## IV. Hybrid Control Behaviors

Control for the Cliff-bot system utilizes CAMPOUT [5] (Control Architecture for Multi-robot Planetary Outposts). This is a decentralized control architecture for controlling systems that require the use of multiple robots to perform a single task. Further information about decentralized control architectures can be found in [6,7]. Higher level control algorithms utilize a hybrid deliberative-reactive control scheme. The hybrid control scheme used by the Cliff-bot system is described in more detail by [8,9].

### *A. Control with combination Velocity Sync and Force Feedback*

The original behavior developed to control the desired tether payout speed for the “Anchor-bots” was denoted as the “Velocity Sync” behavior. This behavior projects the velocity vector of the “Cliff-bot”, shown in (1), along the direction of the tether for the respective “Anchor-bot”. The direction vectors of tethers 1 and 2 are shown in (2) and (3). The dot product of the “Cliff-bot” velocity vector and the direction of the *ith* tether, shown in (4), results in the desired tether payout velocity for the *ith* “Anchor-bot”. In this case, $\theta$ is the “Cliff-bot” heading and $\omega$ is the angular velocity of the “Cliff-bot”. For the “Cliff-bot”, $\omega$ is zero, thus negating the cross-product in (1). Angles $\varphi_i$ and $\beta_i$ are tether yaw and pitch angles as measured by the “Cliff-bot”. These angles are shown in Fig. 5 and Fig. 6. The “Velocity Sync” behavior for the Cliff-bot system was developed by [8,9].

$$\vec{V} = RoverSpeed * [\cos(\theta)\vec{i} + \sin(\theta)\vec{j}] + \omega\vec{k} \times (\vec{r}_{CB\_center} - \vec{r}_{tether\_contact}) \tag{1}$$

$$\vec{T}_1 = -\cos(\phi_1)\cos(\beta_1)\vec{i} + \sin(\phi_1)\cos(\beta_1)\vec{j} \tag{2}$$

$$\vec{T}_2 = -\cos(\phi_2)\cos(\beta_2)\vec{i} - \sin(\phi_2)\cos(\beta_2)\vec{j} \tag{3}$$

$$Tether\_speed_i = \vec{V} \bullet \vec{T}_i \tag{4}$$

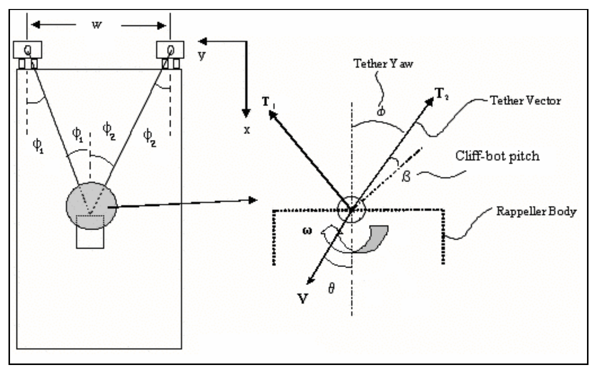


Fig. 5 Illustration of angles known to the Cliff-bot system.

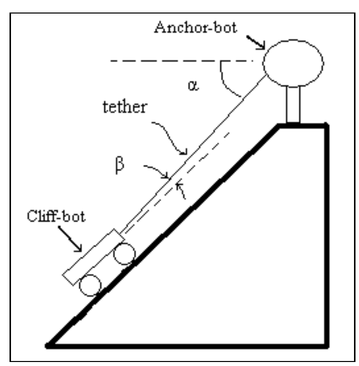


Fig. 6 Pitch angles measured by the “Cliff-bot” and “Anchor-bots”.

After several tests were performed, it became noticeable that the Velocity Sync behavior could not maintain a desirable amount of tension in the tethers. Without taut tethers, there is a highly increased chance for the Cliff-bot system to become unstable. To help correct this issue, load cell sensors were added to each tether to monitor the actual tension in each tether. A control algorithm was then developed that adjusted the tether payout command velocity based on errors in both velocity and tether tension. The block diagram for this controller is shown in Fig. 7. In this case, C1 is the low level PID controller, G(s) represents the system plant, *pm* is the proportion of the "Cliff-bot" mass attached to the respective tether, and W is a constant used to weight the error between the desired and actual force or tension in the respective tether. The desired velocity is then adjusted base on the amount of error in the desired, $F_{des}$, and actual, $F_{act}$, tether tension.

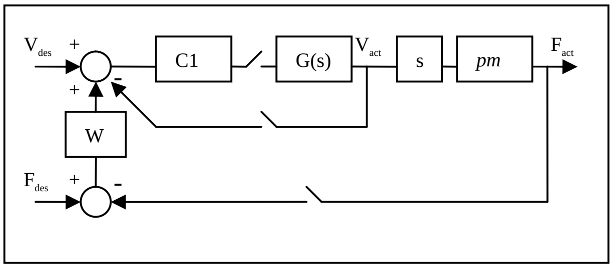


Fig. 7 Block Diagram for controlling tether payout speed.

The Cliff-bot system has the capabilities to measure tether yaw ($\varphi_i$), tether pitch at the Anchor-bots ($\alpha_i$), and tether pitch at the Cliff-bot ($\beta_i$). From this data, along with velocity data from the Cliff-bot , a desired force, or tension, can be computed for each tether. To do this, assume an (x, y) coordinate system in the plane of the tethers, shown in Fig. 5. Then sum the forces in the x and y directions as shown in (5) and (6). In this case, $T_i$ is the tension in the respective tether, $m$ is the mass of the rappelling Cliff-bot , $a_x$ is the acceleration of the Cliff-bot in the x-direction, and $a_y$ is the acceleration of the Cliff-bot in the y-direction. Because the mass of the Cliff-bot" is a known value, and all values of $\varphi_i$ and $a_i$ are measured with sensors, $T_1$ and $T_2$ are the only two unknown terms. Solving (5) and (6) for the desired tether tensions, $T_1$ and $T_2$, results in (7) and (8).

$$\sum F_x : T_1 \cos\phi_1 + T_2 \cos\phi_2 - ma_x = 0 \tag{5}$$

$$\sum F_y : T_1 \sin\phi_1 - T_2 \sin\phi_2 + ma_y = 0 \tag{6}$$

$$T_1 = \frac{ma_x \sin\phi_2 - ma_y \cos\phi_2}{\sin\phi_2 \cos\phi_1 + \sin\phi_1 \cos\phi_2} \tag{7}$$

$$T_2 = \frac{ma_x \sin\phi_1 + ma_y \cos\phi_1}{\sin\phi_2 \cos\phi_1 + \sin\phi_1 \cos\phi_2} \tag{8}$$

Control of the tether payout for the Anchor-bots at JPL is configured, at this point, with the assumption that the Cliff-bot acceleration in the y-direction is negligible. This is done because the Anchor-bots are only required to maintain the static stability of the Cliff-bot for motion along the y-axis. An assumption is also made assuming that the cliff face is a relatively flat surface. That is, the Cliff-bot will not have any tendency to roll about the x-axis. However, if need be, the Cliff-bot roll can be detected based on reading differences between $\beta_1$ and $\beta_2$. With these assumptions, $a_x$ and $a_y$ become (9) and (10) and $T_1$ and $T_2$ become (11) and (12), respectively. In this case, the slope of the cliff face is $\alpha_i$ - $\beta_i$. With this method, motion along the x and y axes is very stable. However, when traversing headings with both x and y components, there are some instabilities that generally causes one wheel of the Cliff-bot to lose contact with the cliff face. Accounting for the Cliff-bot acceleration in the y-direction should help eliminate this issue.

$$a_x = a_{CB} \cos\theta + g \sin(\alpha_i - \beta_i) \tag{9}$$

$$a_y = 0 \tag{10}$$

$$T_1 = \frac{m \sin\phi_2 (g \sin(\alpha_1 - \beta_1) + a_{CB} \cos\theta}{\sin\phi_2 \cos\phi_1 + \sin\phi_1 \cos\phi_2} \tag{11}$$

$$T_2 = \frac{m \sin\phi_1 (g \sin(\alpha_2 - \beta_1) + a_{CB} \cos\theta}{\sin\phi_2 \cos_1 + \sin\phi_1 \cos\phi_2} \tag{12}$$

Comparing the actual Cliff-bot beginning and end position to the desired Cliff-bot beginning and end position is a good way to determine the quality of the controller. Data for the actual Cliff-bot position was collected for 12 runs for motion in the x and y direction. A comparison for the desired and actual Cliff-bot position is shown in Fig. 8 for two runs. In this case, the difference between the x and y displacement for run 2 was 6.78 cm and 3.4 cm, respectively. For run 3, these differences were 1.67 cm and 0.63 cm. The commanded displacement for each of the 12 runs was 100 cm along the x or y-axis. For motion along the x-axis, the average error for the x-displacement was 5.42 % while average diversion along the y-axis was 7.58 cm. For motion along the y-axis, the average error for the y-displacement was 3.91 % while average diversion along the x-axis was 9.49 cm. Error incurred can be a result of several things. However, the largest contribution to error is most likely from small inaccuracies in sensor readings and imprecise control of tether payout velocities.

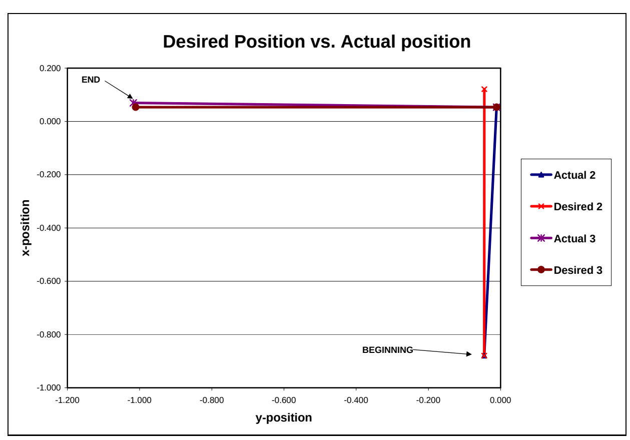


Fig. 8 Error in positional control of the "Cliff-bot" rover.

*B. Control with Force Feedback only*

Another method for controlling the tether payout velocity relies on computing only a desired tether tension. This is opposed to computing both a desired velocity and desired tether tension. The block diagram for this method is shown in Fig. 9. In this case, the only undefined term, C2, is an additional PID controller. At this point, testing has not been performed to prove the "Force Feedback" behavior.

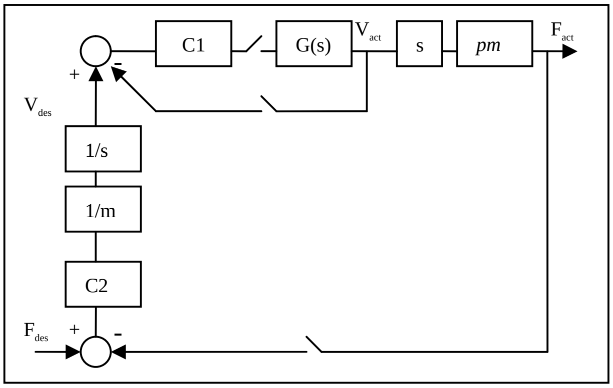


Fig. 9 Block Diagram for controlling desired tether payout velocity based on error in desired ($F_{des}$) and actual ($F_{act}$) tether tensions.

*1) Quasi-Static Force controller*

With a quasi-static force controller, it is assumed that the acceleration due to the Cliff-bot rover is negligible. With this assumption, $a_x$, $a_y$, $T_1$, and $T_2$ become (13), (14), (15), and (16), respectively. With a quasi-static force feedback controller, there is no need for the Anchor-bots to receive any information about the velocity or acceleration of the Cliff-bot . The advantage of this is the elimination of an extra state value to communicate.

$$a_x = g\sin(\alpha - \beta) \tag{13}$$

$$a_y = 0 \tag{14}$$

$$T_1 = \frac{mg\sin(\alpha_1 - \beta_1)\sin\phi_2}{\sin\phi_2\cos\phi_1 + \sin\phi_1\cos\phi_2} \tag{15}$$

$$T_2 = \frac{mg\sin(\alpha_2 - \beta_2)\sin\phi_1}{\sin\phi_2\cos\phi_1 + \sin\phi_1\cos\phi_2} \tag{16}$$

Testing of the quasi-static force controller was performed at JPL with the combination "Velocity Sync" and "Force Feedback" behavior. Because the same assumption for $a_y$ is made for the quasi-static force controller as was made for the combination controller, the "Cliff-bot" motion was stable for movement along the y-axis. However, instabilities began to occur with motion along the x-axis. The primary instability was inadequate tether tension. This caused the leading wheels to lose contact with the cliff face as the "Cliff-bot" moved up the cliff face in the negative x direction. A possible solution to this issue might be to have the "Anchor-bots" assume a larger "Cliff-bot" mass for motion in the negative x direction.

*2) Fully Dynamic Force Controller*

The fully dynamic force controller takes into account all accelerations on the "Cliff-bot". That is, both the x and y components of the "Cliff-bot" acceleration vector are used to compute the desired tether tension. It is still assumed that the "Cliff-bot" will experience negligible roll about the x axis. With these assumptions, $a_x$, $a_y$, $T_1$, and $T_2$ take the form of (17), (18), (19), and (20), respectively. This controller has yet to be tested.

$$a_x = g\sin(\alpha - \beta) + a_{CB}\cos\theta \tag{17}$$

$$a_y = a_{CB}\sin\theta \tag{18}$$

$$T_1 = \frac{m(g\sin(\alpha_1 - \beta_1)\sin\phi_2 + \sin\phi_2 a_{CB}\cos\theta - a_{CB}\sin\theta\cos\phi_2)}{\sin\phi_2\cos\phi_1 + \sin\phi_1\cos\phi_2} \tag{19}$$

$$T_2 = \frac{m(g\sin(\alpha_2 - \beta_2)\sin\phi_1 + \sin\phi_1 a_{CB}\cos\theta + a_{CB}\sin\theta\cos\phi_1)}{\sin\phi_2\cos\phi_1 + \sin\phi_1\cos\phi_2} \tag{20}$$

*C. Fully Implicit Communication*

Another behavior that was investigated was a behavior utilizing fully implicit communication. This refers to an instance where local communication may become lost temporarily between the three rovers. If this were to happen, it is important that the Cliff-bot system is still capable of maintaining stability. By giving the Cliff-bot system some initial values and making a few assumptions, each "Anchor-bot" can imply the necessary unknown values for computing desired tether tension. Also, because permanent magnet direct current motors are used, the "Anchor-bots" also have the ability to sense actual tether tension without the use of special load sensors.

In order for the Implicit Communication behavior to function properly, the Cliff-bot system must be capable maintaining stability by using a quasi-static force controller. This is necessary, because if communication between the rovers were to fail, there would be no way for the rappelling "Cliff-bot" rover to communicate velocity or acceleration data to the two "Anchor-bots". To verify this, the dynamic components of the desired tether tension equation were removed. Thus, only the static tether tension equations were used to compute the desired tether tension in each tether. After implementing the quasi-static assumption into the Cliff-bot system, a test was performed. During this test, the Cliff-bot system was able to maintain stability. However, it was noticeably less stable when compared to the controller that accounts for "Cliff-bot" acceleration along the x-axis.

To use the Implicit Communication behavior, a function must be developed so each "Anchor-bot" can determine the desired tension in the respective tethers. When computing the desired tension of tether 1, $T_1$, there are only two parameters unknown to "Anchor-bot 1". These parameters are $\beta_1$ and $\varphi_2$. In this case, $\beta_1$ is the pitch angle relative to the horizontal axis of the rappelling "Cliff-bot" and $\varphi_2$ represents the yaw of tether 2. For a constant sloped surface, $\beta_1$ is assumed to be approximately zero. To determine $\varphi_2$, the initial distance between the two "Anchor-bots", w, and the initial length of tether 1 are required. From the parameters shown in Fig. 10 equations are derived for determining $\varphi_2$. These equations, shown in (21) through

(24), utilize the laws of cosine and sine. The resulting equation for desired tension in tether 1 is shown in (25). The same technique is used for determining the desired tension in tether 2.

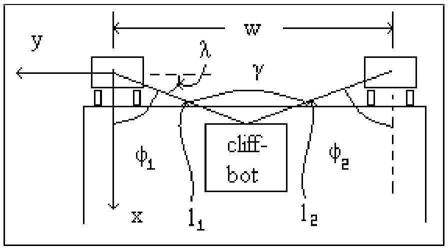


Fig. 10 Parameters for implying yaw angle of tether 2.

$$\lambda = 90 - \phi_1 \tag{21}$$

$$l_2 = \sqrt{w^2 - l_1^2 - 2wl_1 \cos\lambda} \tag{22}$$

$$\gamma = \sin^{-1}\left(\frac{w\sin\lambda}{l_2}\right) \tag{23}$$

$$\phi_2 = \gamma - \phi_1 \tag{24}$$

$$T_1 = \frac{mg\sin\alpha_1}{\cos\phi_1 + \sin\phi_1 / \tan\phi_2} \tag{25}$$

When communication is fully functional, the actual tension in each tether is measured by load cells located on the rappelling "Cliff-bot" rover. Obviously, if communication were to fail, it would not be possible for the "Anchor-bots" to utilize the load cell data. After collecting data on several runs for tension as measured by the load cells and motor current for the winch motors, a constant was found relating the motor current to the tether tension. The resulting comparison between the corrected motor current data, for tension, and the load cell data for tension is shown in Fig. 11. Data for the sensors correlate well. This means that implicit communication is possible. Testing of the Implicit Communication behavior proved that the assumptions made were adequate. The system was able to maintain stability to the same degree as the quasi-static force controller.

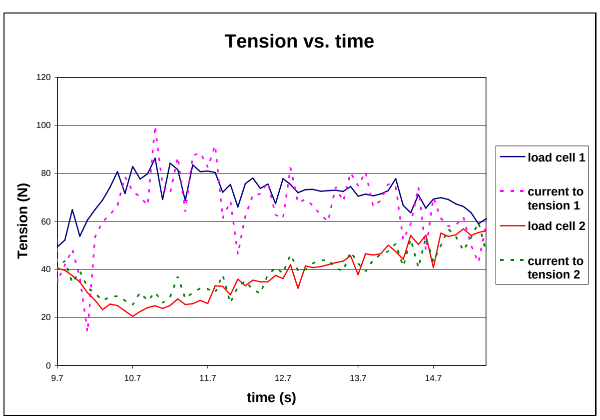


Fig. 11 Comparison of sensors for measuring tether tension.

### D. *Avoid Singularity*

Another hybrid control behavior is the Avoid Singularity behavior. This behavior, developed by [5][6], refers to a singularity that exists in the equations for tether tension. When the Cliff-bot system recognizes that it is approaching the singularity, the Avoid Singularity behavior is initiated. The behavior reacts to the singularity point by commanding the "Anchor-bots" to traverse away from the cliff-edge. The "Anchor-bots" travel a predetermined distance at a predetermined angle before the "Cliff-bot" is allowed to continue its ascent. This behavior, although developed in 2001, was successfully demonstrated on JPL's Cliff-bot system in 2004. Images of this behavior are shown in Fig. 12 (Note the position of the "Anchor-bots").

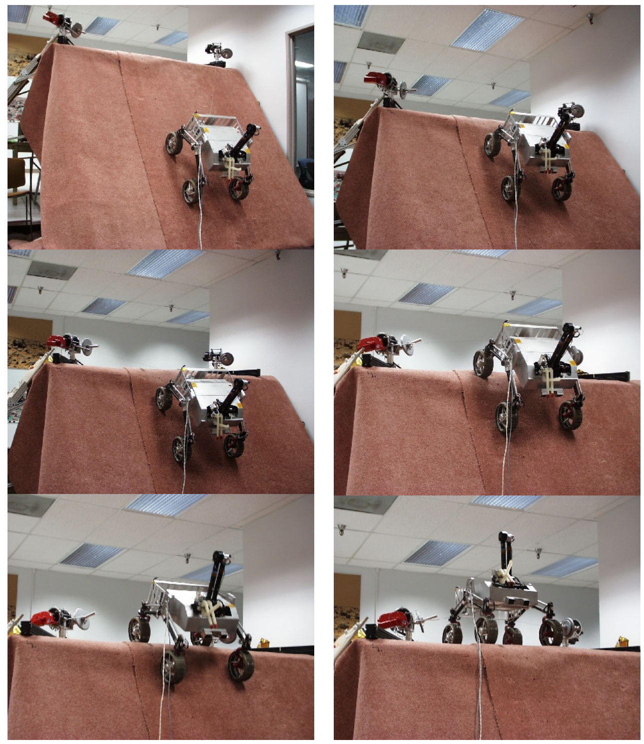

Fig. 12 Demonstration of Avoid Singularity Behavior.

Changes have been made to the reactive part of the Avoid Singularity behavior. Initially the system used data for the tether angles along with tether length to determine when to initiate the Avoid Singularity behavior. The tether angles used were the yaw of the tethers. Originally, the sum of the two yaw angles, $\varphi_1$ and $\varphi_2$, was compared to some maximum value, $\theta_{max}$. This maximum value was set to be a constant. The new method uses a dynamic maximum value that depends on the slope of the cliff face. Also, data from the load cells are also used to determine when the tension in either of the tethers reaches the maximum allowable tether tension, $T_{max}$. When both conditions are met, i.e. the sum of the angles is greater than $\theta_{max}$ and the tether tension is greater than $T_{max}$, the Avoid Singularity behavior is invoked. The theoretical x-displacement of the Cliff-bot and Anchor-bots , as compared with the tether tension and $\varphi_1 + \varphi_2$, is shown in Fig. 13. In this case, it is assumed that the slope of the cliff face is a constant 50 degrees, maximum tether tension is 160 N, gravity is 9.8 m/s$^2$, and $\varphi_1 = \varphi_2$.

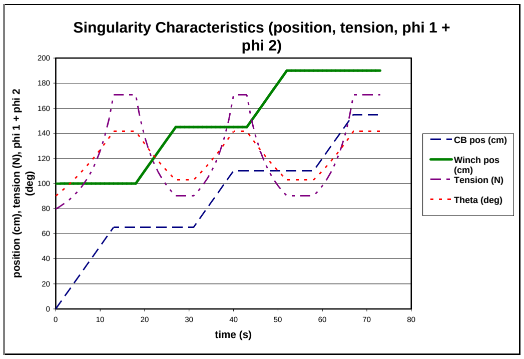


Fig. 13 Graph of Cliff-bot and Anchor-bot displacements along with tether tension and $\varphi_1 + \varphi_2$.

With the assumptions that $\varphi_1$ is equal to $\varphi_2$ and that the slope is constant, the tension in tethers 1 and 2 will also be equivalent. As the “Cliff-bot” traverses up the cliff face, towards the “Anchor-bots”, $\varphi_1 + \varphi_2$ increases along with the tether tension. When $\varphi_1 + \varphi_2$ exceeds $\theta_{max}$ and tension in tether 1 or 2 exceeds $T_{max}$, the “Cliff-bot” pauses its motion and the “Anchor-bots” begin their motion. As the “Anchor-bots” move away from the “Cliff-bot”, $\varphi_1 + \varphi_2$ and tether tension both decrease. After the “Anchor-bots” move a predetermined distance, the “Anchor-bots” pause and the “Cliff-bot” resumes motion up the cliff face. This behavior is repeated, as shown in Fig. 13, until the “Cliff-bot” reaches the desired waypoint.

To find the function for $\theta_{max}$, first assume the tether tension in tether 1 is equal to some maximum tension value, $T_{max}$. For this system, $T_{max}$ is determined from the load restrictions on the tether. Since $\theta_{max} = \phi_1 + \phi_2$, then to solve for $\theta_{max}$, an assumption must be made. This is because there are actually two unknowns, $\varphi_1$ and $\varphi_2$. By assuming $\phi_2 = 90$ degrees and solving for $\varphi_1$, this ensures the absolute minimum value for $\theta_{max}$ at a point where a singularity might exist.

Before solving for $\varphi_1$, one more assumption must be made. This assumption is shown in (26). If this function were less than zero, $\varphi_2$ would also be less than zero for $T_{max}$. Since $0 \le \phi \le 90$ for both tethers, it is impossible for $\varphi_2$ to be negative. After making both assumptions, the function for $\theta_{max}$, shown in (27) was derived. When applied to the conditions for Fig. 13, $\theta_{max}$ becomes 135 degrees.

$$\frac{mg\sin(\alpha_1 - \beta_1)}{T_{max}} - \cos\phi_1 \ge 0 \qquad (26)$$

$$\theta_{max} = \cos^{-1}\left(\frac{mg\sin(\alpha_1 - \beta_1)}{T_{max}}\right) + 90 \qquad (27)$$

## V. Future Work

Although, much has been developed and proven with the Cliff-bot system, there are still a significant number of tasks left to complete. Many tasks can still be developed with the prototype system at JPL. This includes the development of more behaviors to make the system more robust. Also, the building of two new rovers is required in order to make the “Anchor-bots” fully mobile. When this is complete, additional control behaviors will need to be developed to coordinate the motion between all three rovers. More specifically, coordinated motion when the team is traveling to the area of interest.

Some of the behaviors that can be tested include those of “Avoid Tether Catch” and “Maintain Safe Heading”. These behaviors were developed by [8,9] to detect and avoid a tether catch on an obstacle and to detect and avoid the boundary limits on the workspace. Another behavior that can be developed and tested is the “Begin Cliff Descent” behavior. This behavior refers to the beginning motion of the Cliff-bot system when all three rovers are perched at the top of the cliff face. Basically, the Begin Cliff Descent behavior is nearly the opposite of the Avoid Singularity behavior.

## VI. Conclusions

The Cliff-bot system in the current state has proved to be a capable cliff climbing system. In practice, the Cliff-bot system has shown the ability to traverse natural terrain with slopes greater than 60 degrees [4] and laboratory walls of greater than 70 degrees. The system has not been tested on slopes more severe than 70 degrees. The continuous development and testing of control behaviors is proving to make the Cliff-bot system a very robust and autonomous system.

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